

DYNAMIC BEAMFORMING FOR AD HOC NETWORKS

TECHNICAL FIELD

[0001] Implementations consistent with the principles of the invention, relate to the field of wireless communications and, more particularly, to systems and methods for using adaptive antenna arrays to perform dynamic beamforming in wireless networks.

BACKGROUND OF THE INVENTION

[0002] Omnidirectional antennas can detect and generate signals equally well in all directions. Even when a location of a remote communication device is known, however, transmissions to the remote device via an omni-directional antenna can cause energy to be transmitted in wrong directions as well as the right direction. Similarly, when receiving transmissions from a remote device via an omnidirectional antenna, signals from the remote device may be received, as well as interfering signals from devices in different locations around the omnidirectional antenna. The amount of interfering signals may be high, especially if transmitting devices also use omnidirectional antennas.

[0003] A switched beam antenna may transmit or receive signals using one of a number of predetermined beams. The antenna may use any one of the predetermined beams that is expected to provide the strongest signal between the antenna and an intended communication device. Thus, a switched beam antenna may provide less interference than an omnidirectional antenna because signals are not transmitted and received in all directions, but are transmitted and received, more or less, in a direction of interest. Further, because transmission and reception are directed in a particular

direction, the range of transmission and reception may be increased in the particular direction.

[0004] Unlike switched beam antennas, adaptive array antennas do not have predetermined beams. An adaptive array, or electrically steerable, antenna permits a gain pattern to be dynamically modified. Adaptive array antennas include a number of array elements attached to separate antennas. Each array element may transmit or receive a radio frequency (RF) signal simultaneously. Given different gains and/or phases applied to each array element (weights), arbitrary constructive and destructive propagation patterns can effectively be created, thereby causing antenna patterns of gains and nulls.

[0005] Typically, adaptive array antennas are used to steer a beam in a previously known direction. This is a difficult task in a wireless network, such as an ad hoc network in which all nodes are moving and signals may be received from any direction at any time. Therefore, there is a need for an adaptive array antenna that can perform dynamic beamforming on a signal arriving from any direction.

SUMMARY OF THE INVENTION

[0006] Systems and methods consistent with the principles of the invention may receive signals from a transmitting source and determine weights for dynamically adapting elements of an antenna array.

[0007] In a first aspect of the invention, a method for dynamically adjusting a beam of an adaptive antenna array is provided. A receiving node receives, via a group of antenna array elements, a signal from a transmitting node. Each received signal from the antenna array elements is digitized and recorded. $K+1$ output signals are generated from

the recorded digitized signal by applying each of a group of weight sets to the digitized signal. Each of the weight sets corresponds to a different one of k known neighboring nodes and a weight set for generating an omnidirectional propagation pattern. Which one of the $k+1$ output signals to process is determined. The determined one of the $k+1$ output signals is processed and the packet encoded in the one of the $k+1$ output signals is decoded.

[0008] In a second aspect of the invention, a node configured to operate in a wireless network is provided. The node includes a transceiver and a processor connected to the transceiver. The transceiver includes a group of antenna array elements and a memory. The transceiver is configured to receive a signal, from a transmitting node, via the group of antenna array elements, and detect a beginning of a packet in the signal. The transceiver is further configured to store, in the memory, respective portions of the signal received via corresponding ones of the antenna array elements. The processor is configured to access the stored portions of the received signal from the memory and generate output signals based on the stored portions of the received signal. Each of the output signals is generated using a different one of a group of weight sets. The weight sets correspond to k known neighboring nodes and a weight set for generating an omnidirectional propagation pattern. The processor is further configured to determine which one of the $k+1$ output signals to process, process the one of the $k+1$ output signals and decode the packet encoded in the one of the $k+1$ output signals.

[0009] In a third aspect of the invention, a machine-readable medium having instructions recorded thereon for a processor is provided. When the instructions are executed by the processor, the processor is configured to access a group of recorded

waveforms in a memory. Each of the recorded waveforms was received via a different one of a group of antenna array elements. The processor is further configured to apply each of $k+1$ weight sets to the recorded waveforms to generate $k+1$ output signals. K of the weight sets correspond to predetermined weights sets for each of k known neighboring nodes and one of the weight sets is a predetermined weight set for generating an omnidirectional propagation pattern. The processor is further configured to determine which one of the $k+1$ output signals to process and process the determined one of $k+1$ output signals. The processing includes decoding a received packet included in the one of the $k+1$ output signals.

[0010] In a fourth aspect of the invention a node configured to operate in a wireless network is provided. The node includes means for receiving a signal from a transmitting node via a group of antenna array elements, means for storing a representation of the received signal, means for generating a group of output signals by applying each of a group of weight sets to the representation of the received signal, where k of the weight sets correspond to k known neighboring nodes and one of the weight sets is a predetermined weight set for propagating an omnidirectional pattern, means for determining which one of the output signals to process, and means for processing and for decoding the determined one of the plurality of output signals.

BRIEF DESCRIPTION OF THE DRAWINGS

[0011] The accompanying drawings, which are incorporated in and constitute a part of this specification, illustrate an embodiment of the invention and, together with the description, explain the invention. In the drawings,

[0012] Fig. 1 illustrates an exemplary ad hoc network that may be used with implementations consistent with principles of the invention;

[0013] Fig. 2 is a block diagram of a node, consistent with the principles of the invention;

[0014] Fig. 3 is a detailed block diagram of a receiving portion of a transceiver consistent with the invention;

[0015] Figs. 4A-4B are flowcharts that illustrate processing in an implementation of a node consistent with the principles of the invention;

[0016] Fig. 4C is a portion of a flowchart that illustrates processing in an alternative implementation of a node consistent with the principles of the invention;

[0017] Figs. 5A-5B are flowcharts that illustrate processing in another implementation of a node consistent with the principles of the invention; and

[0018] Fig. 5C is a portion of a flowchart that illustrates processing in an alternative implementation of a node consistent with the principles of the invention.

DETAILED DESCRIPTION

[0019] The following detailed description of the invention refers to the accompanying drawings. The same reference numbers in different drawings may identify the same or similar elements. The following detailed description does not limit the invention. Instead, the scope of the invention is defined by the appended claims and equivalents.

Operating Environment

[0020] One type of wireless network is an “ad-hoc” network. In an ad-hoc network, nodes may cooperatively route traffic among themselves. Network nodes in these

networks may not be permanent: they are, instead, based on whether signals can be adequately decoded between two nodes. The network may adjust dynamically to changing node conditions, which may result from node mobility or failure.

[0021] In general, some or all of the nodes in an ad-hoc network are capable of network routing functions (“routers”), while other nodes may be merely source or destinations for data traffic (“endpoints”). All nodes in the network may execute a set of algorithms and perform a set of networking protocols that enable the nodes to find each other, determine paths through the network for data traffic from source to destination, and detect and repair ruptures in the network as nodes move, fail, as battery power changes, and as communication path characteristics change over time.

[0022] Fig. 1 is a diagram illustrating an exemplary ad-hoc network 100 in which implementations consistent with principles of the invention may operate. Ad-hoc network 100 may include a number of nodes 101-1 through 101-16 (collectively referred to as nodes 101). Lines joining nodes 101 represent connectivity; that is, if two nodes 101 are connected by a line, the two nodes can communicate directly with one another. A message in network 100 can make its way through the network, hop-by-hop, until it reaches its destination node.

Exemplary Hardware Configuration

[0023] Fig. 2 illustrates an exemplary configuration of node 101 that may be used in network 100. Exemplary node 101 may include a processor 202, a memory 204, a bus 206, a transceiver 208, a power supply 210, and a sensor 212.

[0024] Processor 202 may be a conventional microcomputer, micro-controller, Digital Signal Processor (DSP), logic, such as a Field Programmable Gate Array (FPGA)

or Application Specific Integrated Circuit (ASIC), or any other device capable of controlling node 101 and processing signals.

[0025] Memory 204 may include static memory, such as Nonvolatile Random Access Memory (NVRAM) or flash memory for storing instructions and configuration parameters. Memory 304 may also include Dynamic Random Access Memory (DRAM), or any other convenient form of memory for use as working storage during operation of node 101.

[0026] Bus 206 may provide a path through which the various components of node 101 may communicate with one another.

[0027] Transceiver 208 may include a receiving portion and a transmitting portion that are capable of modulating messages via radio frequency (RF) over a wireless channel. In one implementation, transceiver 208 may perform such functions as converting bits to chips, inserting preambles (for example, to provide synchronization patterns for a receive modem), adding error correction features, such as Forward Error Correction codes, and providing power level indications.

[0028] Transceiver 208 also may be capable of demodulating messages received by an antenna. In one implementation, transceiver 208 may perform functions, such as detection of synchronization preambles, Viterbi decoding, and application of error codes.

[0029] Sensor 212 may optionally be provided for sensor network nodes. Sensor 212 may include a video sensor, for still or moving images, an acoustic sensor, a magnetic sensor, or other types of sensors. An ad hoc wireless sensor network may, for example, be used to gather environmental data for a particular area in which the nodes are placed.

[0030] Power supply 210 may be provided to power node 101. Power supply 210 may include, for example, one or more batteries, solar collectors, and ambient energy scavengers.

[0031] Fig. 3 provides a more detailed view of a receiving portion 208-R of transceiver 208. Receiving portion 208-R may include antenna array elements 302-1 through 302-L (collectively referred to as antenna array elements 302), downconverters 304-1 through 304-L (collectively referred to as downconverters 304), analog-to-digital (A/D) converters 306-1 through 306-L (collectively referred to as A/D converters 306), and memories 308-1 through 308-L (collectively referred to as memories 308). The receiving portion of transceiver 208, shown in Fig. 3 is exemplary and may have more, fewer, or different components than as illustrated in Fig. 3.

[0032] RF signals may be received via antenna elements 302 and may be passed to respective downconverters 304 for conversion from RF to a baseband frequency signals. A/D converters 308 may convert the baseband signals from respective downconverters 304 from analog form to digital form. The digital signals may then be stored in respective memories 308.

[0033] In other implementations, memories 308 may be one memory accessible by all A/D converters 306.

Exemplary Operation

[0034] Each node 101 in an ad hoc network may periodically transmit heartbeat packets (or “beacons”). Each heartbeat packet transmitted by node 101 may include an identifier of transmitting node 101, identifiers of neighboring nodes 101 from which transmitting node 101 has recently received a heartbeat packet, a location of transmitting

node 101 ($p_{reported}$) and a velocity of transmitting node 101 ($v_{reported}$). Transmitting node 101 may determine its location via an on-board global positioning system (GPS) and may determine an expected velocity vector by, for example, extrapolation from previous locations, or by on-board mission plans.

[0035] When receiving node 101 receives a heartbeat packet from a neighboring node 101, receiving node 101 may update a table of reported positions and velocities of all currently known neighboring nodes 101. When node 101 determines that any of neighboring nodes 101 have not been heard from for a predetermined period of time, unheard-from neighboring nodes 101 are assumed to be gone and node 101 may remove location and velocity information, pertaining to the unheard-from neighboring nodes 101, from the table of reported positions and velocities. As will be discussed below, each node 101 may maintain a set of weights corresponding to each known neighboring node 101. When node 101 removes location and velocity information pertaining to an unheard-from neighboring node 101, node 101 may also remove the weight set corresponding to the unheard-from neighboring node 101.

[0036] Assuming that an adaptive antenna array has L elements, the L elements may detect a beginning and ending of a signal that may include an arriving packet. Antenna array elements 302 may detect the signal by detecting an RF signal having at least a predetermined signal strength coupled with detection of at least some acquisition and timing bits that may be included in a header of each packet. When a packet is detected, each antenna array element 302-1 through 302- L may pass the received signal to a different downconverter 304. Downconverters 304 may downconvert the received signal from RF to baseband frequency and may pass the downconverted signal to different A/D

converters 306. A/D converters 306 may digitize the downconverted signals and may record the digitized signal (or waveform) in memories 308. Once a complete waveform is recorded in memories 308, processor 202 may access the waveform in memories 308 via bus 206 and may generate a group of output signals. Processor 202 may then select an error-free one of the output signals for further processing. We refer to this approach as a “store-and-process” approach. Alternatively, to improve latency, processor 202 may access the waveforms after enough, but not necessarily all, of the waveform has been recorded in memories 308, generate a group of output signals and select a strongest signal from the group of output signals for further processing. We refer to this approach as a “process-live” approach.

[0037] After hearing from a neighboring node 101, processor 202 may update its internal estimate of a location of neighboring node 101 and may create a set of weights, w , for known neighboring node 101. The sets of weights, w , for all k known neighboring nodes, as well as a weight set for an omnidirectional pattern may be stored in memories 308 and/or memory 204. Upon initialization, only the omnidirectional weight set may be known and stored in memories 308 and/or memory 204. The weight sets, w , may be created to maximize gain in a direction of transmitting node 101, while minimizing gain (maximizing null) in directions of all other known neighbors. A number of techniques are well known and may be used for deriving the weight sets, w . After at least enough of a received signal, received via antenna array elements 302, has been received and stored, processor 202 may access the stored received signal and may apply each of the $k+1$ weight sets to the received signal to generate $k+1$ output signals. Each weight set includes L weights, one weight corresponding to each of the L antenna array elements

302. When using the “store-and-process” approach, processor 202 may determine a first one of the $k+1$ output signals that is received error-free and provide that signal to the system for further processing. When using the “process live” approach, processor 202 may determine a strongest output signal from among the $k+1$ output signals and provide that signal for further processing. Using either approach, processor 202 may then determine whether the received packet is a heartbeat packet, including location information and velocity information. If the received packet is a heartbeat packet, then processor 202 may determine whether receiving node 101 has a line-of-sight connection with transmitting node 101. The weight set corresponding to the transmitting node 101 may then be updated based on an expected position of transmitting node 101 between transmission of heartbeat messages, as described in more detail below.

Exemplary Processing (“Store-and-Process” Approach)

[0038] Figs. 4A and 4B are flowcharts that illustrate exemplary processing in node 101 consistent with the principles of the invention. Processing may begin with receiver portion 208-R of transceiver 208 detecting a beginning of an arriving packet. Each of L antenna array elements 302 may receive an RF signal (waveform), respective downconverters 304 may downconvert the respective received signal to baseband frequency, each respective A/D converter 306 may convert the respective baseband signal to digital form, and each respective memory 308 may record the received waveform from corresponding A/D converter 306 (act 402). Thus, each of L antenna array elements 302 may receive the waveform and the waveform received, via each of the L antenna array elements 302, may be recorded to memories 308. After all of the waveform has been recorded, processor 202 may access the recorded waveform in memories 308 and weight

sets, w , of k known neighbors to generate k output signals, where k is a number of known neighboring nodes 101. Processor 202 may generate a $(k+1)^{\text{st}}$ output signal using a stored set of weights for an omnidirectional propagation pattern. Each output signal is generated by applying a weight set to a waveform received via antenna array elements 302. The output signals corresponding to the k known neighbors may be of the form $y_k(t) = w_k^H x(t)$, where w_k^H is a complex conjugate of a transpose of a vector of all L signals (assuming there are L antenna array elements 302) and $x(t)$ is the transpose of the vector of all L signals (act 404).

[0039] After generating the $k+1$ output signals, processor 202 may find a first one of the $k+1$ output signals that is received error-free and may pass the error-free output signal to other processes within node 101 for further processing (act 406). Processor 202 may then decode the received packet included in the output signal and may determine whether the packet included in the selected output signal is a heartbeat packet (act 408). If the packet is not a heartbeat packet, then the exemplary process is completed. If the packet is a heartbeat packet, then processor 202 may determine which of the $k+1$ output signals is strongest (act 410). Note that when receiving node 101 receives a signal from a previously unknown node, the output signal corresponding to the omnidirectional propagation pattern may be the strongest signal because the signal is being received from an unexpected node position. Processor 202 may calculate an estimated angle (p_{calc}) to the transmitting node (act 411). Processor 202 may calculate estimated angle (p_{calc}) by using a well-known technique in which eigenvalues of an array correlation matrix are used. If receiving node 101 has line-of-sight connectivity, then p_{calc} is the direction of

transmitting node 101. If the line-of-sight is obscured, then p_{calc} may be a direction of a strongest multipath signal.

[0040] In order to determine whether p_{calc} is the estimated angle to transmitting node 101, processor 202 may determine whether p_{calc} corresponds to a reported position of the transmitting node 101 ($p_{reported}$) which may be included in the received heartbeat message (act 412: Fig. 4B). If p_{calc} corresponds to $p_{reported}$, then receiving node 101 has line-of sight connectivity to transmitting node 101 and reported velocity ($V_{reported}$) from the received heartbeat message, is used to estimate a position of transmitting node 101 between heartbeat messages (act 414).

[0041] If p_{calc} does not correspond to $p_{reported}$, then a multipath signal was received and the reported location of transmitting node 101 may not be used as an accurate estimator of the best propagation pattern to use to receive signals from transmitting node 101. Processor 202 may then determine whether $V_{reported}$ equals 0 (act 416). If $V_{reported}$ is 0, then transmitting node 101 may not be moving and processor 202 may use a last known location of transmitting node 101 to estimate a position of transmitting node 101 (act 418). Thus, for rapidly moving vehicles, implementations consistent with the principles of the invention may assume that a vector between a transceiver of transmitting node 101 and a transceiver of receiving node 101 will generally be a more reliable direction than any temporary multipath signal direction.

[0042] If processor 202 determines that $V_{reported}$ is not 0, then the transmitting node is moving and processor 202 may send information regarding past movement of the transmitting node through a Kalman filter, or a similar predictive filter that may be implemented by processor 202, to estimate a position of transmitting node 101 (act 420).

Processor 202 may use uncertainty of the estimate by the predictive filter to determine a width of a beam pattern to generate.

[0043] Processor 202 may then update the weight set, w , corresponding to transmitting node 101, based on the estimated position of transmitting node 101 (from acts 418, 420 or from act 414) (act 422). Any well-known technique may be used to update the weight set, w .

[0044] Alternatively, when processor 202 determines that p_{calc} does not correspond to $p_{reported}$ (act 412), processor 202 may use the last known position of transmitting node 101 to estimate a position of the transmitting node (act 418), as illustrated in Fig. 4C.

Exemplary Processing (“Process-Live” Approach)

[0045] Figs. 5A and 5B are flowcharts that illustrate exemplary processing in node 101 consistent with the principles of the invention. Processing may begin with receiver portion 208-R of transceiver 208 detecting a beginning of an arriving packet. Each of L antenna array elements 302 may receive an RF signal (waveform), respective downconverters 304 may downconvert the respective received signal to baseband frequency, each respective A/D converter 306 may convert the respective baseband signal to digital form, and each respective memory 308 may record the received waveform from corresponding A/D converter 306 (act 502). Thus, each of L antenna array elements 302 may receive the waveform and the waveform received, via each of the L antenna array elements 302, may be recorded to memories 308. After at least a portion of the waveform has been recorded, processor 202 may access the recorded waveform in memories 308 and weight sets, w , of k known neighbors to generate k output signals, where k is a number of known neighboring nodes 101. Processor 202 may generate a

$(k+1)^{\text{st}}$ output signal using a stored set of weights for an omnidirectional propagation pattern. Each output signal is generated by applying a weight set to a waveform received via antenna array elements 302. As described previously, the output signals corresponding to the k known neighbors may be of the form $y_k(t) = w_k^H x(t)$, where w_k^H is a complex conjugate of a transpose of a vector of all L signals (assuming there are L antenna array elements 302) and $x(t)$ is the transpose of the vector of all L signals (act 504).

[0046] After generating the $k+1$ output signals, processor 202 may find a strongest one of the $k+1$ output signals that is received and may pass the strongest output signal to other processes within node 101 for further processing (act 406). Processor 202 may then decode at least the received portion of a packet included in the strongest output signal and may determine whether the packet included in the strongest output signal is a heartbeat packet (act 508). If the packet is not a heartbeat packet, then the exemplary process is completed. If the packet is a heartbeat packet, then processor 202 may calculate an estimated angle (p_{calc}) to the transmitting node (act 510). Processor 202 may calculate estimated angle (p_{calc}) by using a well-known technique in which eigenvalues of an array correlation matrix are used. If receiving node 101 has line-of-sight connectivity, then p_{calc} is the direction of transmitting node 101. If the line-of-sight is obscured, then p_{calc} may be a direction of a strongest multipath signal. Note that when receiving node 101 receives a signal from a previously unknown node, the output signal corresponding to the omnidirectional propagation pattern may be the strongest signal because the signal is being received from an unexpected node position.

[0047] In order to determine whether p_{calc} is the estimated angle to transmitting node 101, processor 202 may determine whether p_{calc} corresponds to a reported position of the transmitting node 101 ($p_{reported}$) which may be included in the received heartbeat message (act 512; Fig. 5B). If p_{calc} corresponds to $p_{reported}$, then receiving node 101 has line-of sight connectivity to transmitting node 101 and reported velocity ($V_{reported}$) from the received heartbeat message, is used to estimate a position of transmitting node 101 between heartbeat messages (act 514).

[0048] If p_{calc} does not correspond to $p_{reported}$, then a multipath signal was received and the reported location of transmitting node 101 may not be used as an accurate estimator of the best propagation pattern to use to receive signals from transmitting node 101. Processor 202 may then determine whether $V_{reported}$ equals 0 (act 516). If $V_{reported}$ is 0, then transmitting node 101 may not be moving and processor 202 may use a last known location of transmitting node 101 to estimate a position of transmitting node 101 (act 518). Thus, for rapidly moving vehicles, implementations consistent with the principles of the invention may assume that a vector between a transceiver of transmitting node 101 and a transceiver of receiving node 101 will generally be a more reliable direction than any temporary multipath signal direction.

[0049] If processor 202 determines that $V_{reported}$ is not 0, then the transmitting node is moving and processor 202 may send information regarding past movement of the transmitting node through a Kalman filter, or a similar predictive filter that may be implemented by processor 202, to estimate a position of transmitting node 101 (act 520). Processor 202 may use uncertainty of the estimate by the predictive filter to determine a width of a beam pattern to generate.

[0050] Processor 202 may then update the weight set, w , corresponding to transmitting node 101, based on the estimated position of transmitting node 101 (from acts 518, 520 or from act 514) (act 522). Any well-known technique may be used to update the weight set, w .

[0051] Alternatively, when processor 202 determines that p_{calc} does not correspond to $p_{reported}$ (act 512), processor 202 may use the last known position of transmitting node 101 to estimate a position of the transmitting node (act 518), as illustrated in Fig. 5C.

Variations

[0052] The exemplary processing of Figs. 4A-4C and 5A-5C illustrates that when a heartbeat packet is received, further processing is performed. Alternatively, $V_{reported}$ and $p_{reported}$ may be provided, for example, in a header field in other packets, or possibly all packets. Thus, instead of checking whether a heartbeat packet is received, (act 408: Fig. 4A and act 508: Fig. 5A) processor 202 may, instead, check whether the received packet includes $V_{reported}$ and $p_{reported}$, and if so, processor 202 may continue processing of acts 411-422 (Fig. 4B) or acts 511-522 (Fig. 5B), as previously described.

Conclusion

[0053] Systems and methods consistent with the principles of the invention dynamically determine a best direction for a gain or a null after or during a time when a signal is being received from a transmitting node. Implementations consistent with the principles of the invention reduce multiple access interference, improve signal strength, and thereby, improve a network's data carrying capacity.

[0054] The foregoing description of preferred embodiments of the invention provides illustration and description, but is not intended to be exhaustive or to limit the invention

to the precise form disclosed. Modifications and variations are possible in light of the above teachings or may be acquired from practice of the invention for example, while series of acts have been described with regard to Figs. 4A-4C and 5A-5C, the order of the acts may differ in other implementations consistent with the present invention. Also, non-dependent acts may be performed in parallel. In addition, although implementations of the invention were described as applying to a wireless ad hoc network, implementations of the invention are not limited to wireless ad hoc networks. For example, implementations consistent with the principles of the invention may be used with other types of wireless networks, such as, a wireless network that uses base stations (e.g., a cell phone tower system).

[0055] No element, act, or instruction used in the description of the present application should be construed as critical or essential to the invention unless explicitly described as such. Also, as used herein, the article “a” is intended to include one or more items. Where only one item is intended, the term “one” or similar language is used. The scope of the invention is defined by the claims and their equivalents.